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Development of the Universe and New Cosmology

A.S. Sakharov^{ab} and H. Hofer^a

^a*Swiss Institute of Technology, ETH-Zuerich, 8093 Zuerich, Switzerland*

^b*TH Division, CERN, 1211 Geneva 23, Switzerland*

Abstract

Cosmology is undergoing an explosive period of activity, fueled both by new, accurate astrophysical data and by innovative theoretical developments. Cosmological parameters such as the total density of the Universe and the rate of cosmological expansion are being precisely measured for the first time, and a consistent standard picture of the Universe is beginning to emerge. Recent developments in cosmology give rise the intriguing possibility that all structures in the Universe, from superclusters to planets, had a quantum-mechanical origin in its earliest moments. Furthermore, these ideas are not idle theorizing, but predictive, and subject to meaningful experimental test. We review the concordance model of the development of the Universe, as well as evidence for the observational revolution that this field is going through. This already provides us with important information on particle physics, which is inaccessible to accelerators.

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1 Introduction

Our present understanding of the Universe is based upon the successful hot Big Bang theory, which explains its evolution from the first fraction of a second to our present age, around 13 billion years later. This theory rests upon four strong pillars, a theoretical framework based on general relativity, as put forward by Albert Einstein [1] and Alexander A. Friedmann [2] in the 1920s, and three robust observational facts: First, the expansion of the Universe, discovered by Edwin P. Hubble [3] in the 1930s, as a recession of galaxies at a speed proportional to their distance from us. Second, the relative abundance of light elements, explained by George Gamow [4] in the 1940s, mainly that of helium, deuterium and lithium, which were cooked from the nuclear reactions that took place at around a second to a few minutes after the Big Bang, when the Universe was a few times hotter than the core of the Sun. Third, the cosmic microwave background (CMB), the afterglow of the Big Bang, discovered in 1965 by Arno A. Penzias and Robert W. Wilson [5] as a very isotropic black-body radiation at a temperature of about 3 degrees Kelvin, emitted when the Universe was cold enough to form neutral atoms and photons decoupled from matter, approximately 400,000 years after the Big Bang. Today, these observations are confirmed to within a few per cent accuracy, and have helped establish the paradigm of inflationary hot Big Bang cosmology as the preferred model of the Universe [6].

2 The Universe as we see it

All of modern cosmology stems essentially from an application of the Copernican principle: we are not at the centre of the Universe. In fact, today we take Copernicus' idea one step further and assert the “cosmological principle”: *nobody* is at the centre of the Universe. The cosmos, viewed from any point, looks the same as when viewed from any other point. This, like other symmetry principles more directly familiar to particle physicists, turns out to be an immensely powerful idea. In particular, it leads to the apparently inescapable conclusion that the Universe has a finite age. There was a beginning of time.

This cosmological principle can be expressed by applying one of the most “reasonable” symmetries to the Einstein equation, which initially connects the geometry of space-time with the matter content of the Universe. The simplest symmetries of this type are *homogeneity* and *isotropy*. By homogeneity, we mean that the Universe is invariant under spatial translations, while isotropy implies invariance under rotations. In this sense the contents of the Universe can be modelled as a perfect fluid with some equation of state ¹. While this is certainly a poor description of the contents of the Universe on small scales, such as the size of people or planets or even galaxies, it is an excellent approximation if we average over extremely large scales in the Universe, for which the matter is known observationally to be very smoothly

¹The equation of state is frequently given by a relation between density ρ and pressure p of the fluid.

distributed.

General relativity combined with homogeneity and isotropy leads to a startling conclusion: space-time is dynamic. The Universe is not static, but is bound to be either expanding or contracting. Indeed, in 1929, Hubble undertook a project to measure the distances to the spiral “nebulae”, as they had been known. Hubble’s method involved using Cepheid variables. Cepheid variables have the useful property that the period of their variation is correlated to their absolute brightness. Therefore, by measuring the apparent brightness and the period of a distant Cepheid, one can determine its absolute brightness and therefore its distance. Hubble applied this method to a number of nearby galaxies, and determined that almost all of them were receding from the Earth. Moreover, the more distant the galaxy was, the faster it was receding, according to a roughly linear relation: $v = H_0 d$. This is the famous Hubble law, and the constant H_0 is known as Hubble’s constant. The current best estimate, determined using the Hubble space telescope to resolve Cepheids in galaxies at unprecedented distances, is $H_0 = 71 \pm 6 \text{ km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}$ ² [14]. In any case, the Hubble law is exactly what one would expect from the so-called expanding Friedmann–Robertson–Walker (FRW) Universe [7].

The expansion of the Universe leads to a number of interesting effects. One is the cosmological redshift of photons. The usual way to see this is that, from the Hubble law, distant objects appear to be receding at a velocity $v = H_0 d$, which means that photons emitted from the body are redshifted by the recession velocity of the source. There is another way to look at the same effect: because of the expansion of space, the wavelength of a photon increases with the scale factor: $\lambda \propto a(t)$, so that a photon, propagating in the space as the universe expands, gets shifted to longer and longer wavelengths. The redshift z of a photon is then given by the ratio of the scale factor today to the scale factor when the photon was emitted: $1 + z = \frac{a(t_0)}{a(t_{\text{em}})}$. This redshifting due to expansion applies to particles other than photons as well. For some massive body moving relative to the expansion with some momentum p , the momentum also “redshifts”: $p \propto \frac{1}{a(t)}$. We then have the remarkable result that freely moving bodies in an expanding Universe eventually come to rest relative to the expanding coordinate system. Thus the expansion of the Universe creates a kind of dynamical friction for everything moving in it. If we take a bunch of particles with temperature T in thermal equilibrium, the momenta of all these particles will decrease linearly with the expansion, and the system will cool. For a gas in thermal equilibrium, the temperature is in fact inversely proportional to the scale factor: $T \propto \frac{1}{a(t)}$. The current temperature of the Universe is $2.725 \pm 0.005 \text{ K}$ [20].

One of the things that cosmologists most want to measure accurately is the total density ρ of the Universe. This is very often expressed in units of the critical density needed to make the geometry of the Universe flat. Observers have made attempts to measure the density of the Universe using a variety of methods, including measuring galactic rotation curves, the velocities of galaxies orbiting in clusters, X-ray measurements of galaxy clusters, the velocities and spatial distribution of galaxies on large scales, and gravitational lensing. These measurements have repeatedly pointed

²The *parsec* is a spatial astronomical unit corresponding to one second of arc of the parallax measured from opposite sides of the earth’s orbit: $1 \text{ pc} = 3 \cdot 10^{18} \text{ cm}$.

to the existence of a large amount of dark matter, different from the baryonic constituents of stars and planets. Moreover two groupes - the Supernova Cosmology Project [8] and the High-z Supernova Search Team [9] has recently arrived at a picture of the Universe with flat geometry: matter, including both baryons and the mysterious dark matter, makes up only about 30% of the energy density in the Universe. The remaining 70% is made of something that looks very much like a fluid with negative pressure, which slightly accelerate the current expansion of the Universe ³. This *dark energy* can possibly be identified with the vacuum energy predicted by quantum field theory, except that the energy density is 120 orders of magnitude smaller than would be expected from a naive analysis. This density budget of the Universe, where the critical density is distributed between the following contributions: $4.7 \pm 0.6\%$ luminous matter, $24 \pm 7\%$ dark matter and $71.3 \pm 8\%$ of dark energy, gets confirmed at very high confidence level by recent fascinating results of the WMAP satellite, which in fact "took a picture" of the Universe when it was only about 400,000 years old.

3 Thermal history of the Universe and beyond

The basic picture of an expanding, cooling Universe leads to a number of startling predictions: the formation of nuclei with its resulting primordial abundances of elements, and the later formation of neutral atoms with the consequent presence of a cosmic background of photons [15, 16].

As we go back in time, the Universe becomes hotter and hotter and thus the amount of energy available for particle interactions thus increases. As a consequence, the nature of interactions goes from those described at low energy by long-range gravitational and electromagnetic physics, to atomic physics, nuclear physics, all the way to high energy physics at the electroweak scale, gran unification (perhaps), and finally quantum gravity.

The way we know about the high energy interactions of matter is via particle accelerators, which are unravelling the details of these fundamental interactions as we increase their energy. However, one should bear in mind that the physical conditions that take place in our high energy colliders are very different from those that occurred in the early Universe: these machines could never reproduce the conditions of density and pressure in its rapidly expanding thermal plasma. Nevertheless, those experiments are crucial in understanding the nature and *rate* of the local fundamental interactions available at those energies. What interests cosmologists is the statistical and thermal properties that such a plasma should have, in particular the time at which certain particles *decoupled* from the plasma, i.e. when their interactions were not quick enough with respect to the expansion of the Universe, and they were left out of equilibrium with the plasma.

³Deeper and more precies supernova measurements [10] confirm this conclusion. Future data on supernova from space based [11, 12] and ground based [13] telescopes promise to yield substantial information on the history of cosmic acceleration, and to constrain possible models for the dark energy.

One can trace the evolution of the universe from its origin till today. According to the best accepted view, the Universe must have originated at the Planck era (10^{19} GeV, 10^{-43} s), from a quantum gravity fluctuation. Needless to say, quantum gravity phenomena are still in the realm of physical speculation, although the last astrophysical probes can already feel effects of quantum gravity at the energy level of the Grand Unified Theories (GUTs), about 10^{16} GeV (10^{-35} s) [17] and beyond [18]. However, it is plausible that a pre Big Bang era of cosmological *inflation* originated then. The idea of inflation, a period of accelerated expansion before the FRW expansion is established, provides an elegant solution to set up the initial conditions for standard Big Bang cosmology [19]. At some early time, just before the Universe may have reached the GUTs era (10^{16} GeV, 10^{-35} s) and was not yet thermalized, the energy density of the Universe was dominated by some material (*inflaton field*) with negative pressure. Under such an assumption, the Einstein equation leads to the conclusion that during the pre Big Bang era the expansion of the Universe was exponentially accelerated, spreading out the conditions that took place in a small causally connected region over a huge distance across which we observe the Universe now. The last consequence explains, in particular, how became the Universe so big and so uniform before becoming the FRW Universe.

Quantum fluctuations of the inflaton field then left their imprint as tiny perturbations in an otherwise very homogeneous patch of the Universe. One of the most astonishing predictions of inflation is that quantum fluctuations of the inflaton field, being stretched by the exponential expansion generate large-scale perturbations of the space-time geometry. Patterns of perturbations in the geometry are like fingerprints that unequivocally characterize a period of inflation. When matter falls in the gravitational wells of the patterns, it creates density perturbations that collapse gravitationally to form galaxies, clusters and superclusters of galaxies. Perhaps the most intriguing aspect of modern cosmology is the fact that the large-scale structure was seeded at the extremely early epoch of the development of the Universe, when even the conception of matter in usual sense did not exist yet. Moreover this fact is already tested observationally at a very high level of accuracy by the combination of recent results from WMAP satellite [20] and the 2dF galaxy redshift survey [21].

At the end of inflation, the huge energy density of the inflaton field was converted into particles, which soon thermalized and became the origin of the hot Big Bang. Such a process is called *reheating* of the Universe. Since then, the Universe became radiation-dominated.

It is probable (although by no means certain) that the asymmetry between matter and antimatter originated at the same time as the rest of the energy of the Universe, from the decay of the inflaton. This process is known under the name of *baryogenesis* [22], since baryons (mostly quarks at that time) must have originated then, from the leftovers of their annihilation with antibaryons. Any mechanism of baryogenesis requires a violation of the baryon number, C and CP violation, and a departure from thermal equilibrium [23]. The first two conditions can be discussed only within a particle physics model that is definitely beyond the Standard Model. This fact represents perhaps the best example of the perfect interplay between cosmology and particle physics.

As the Universe cooled down, it may have gone through the quark–gluon phase transition (10^2 MeV, 10^{-5} s), when baryons (mainly protons and neutrons) formed from their constituent quarks [26]. A minor contribution of antimatter regions, which might be left from baryogenesis, can evolve into condensed antimatter objects; these are important footprints of early phase transitions, which took place far above electroweak energies [24]. In this sense the search for antimatter in space, with the AMS-02 experiment [25], turns out to be an important step into a deeper understanding of physics beyond the Standard Model which took place in the early Universe.

The furthest window we have on the early Universe at is for the moment that of *primordial nucleosynthesis* (1–0.1 MeV, 1 s – 3 min), when protons and neutrons were cold enough that bound systems could form, giving rise to the lightest elements, soon after *neutrino decoupling*. It is the realm of nuclear physics. The observed relative abundances of light elements are in agreement with the predictions of the hot Big Bang theory. Immediately afterwards, electron–positron annihilation occurs (0.5 MeV, 1 min) and all their energy goes into photons. Much later, at about 1 eV, $\sim 10^5$ yr, matter and radiation have equal energy densities. Soon after, electrons become bound to nuclei to form atoms (0.3 eV, 3×10^5 yr), in a process known as *recombination*: this is the realm of atomic physics.

Immediately after, photons decouple from the plasma, travelling freely thereafter. Those are the photons we observe as the CMB. The COBE satellite [27] launched in 1990 observed a tiny anisotropy in the angular distribution of the CMB temperature. It is believed that this anisotropy represents intrinsic fluctuations in the CMB itself, due to the presence of tiny primordial density fluctuations in the cosmological matter present at the time of recombination. These density fluctuations are of great physical interest, because these are the fluctuations that later collapsed to form all of the structures in the Universe, from superclusters to planets. Moreover the angular distribution of the CMB depends, for example, on the baryon density, the Hubble constant H_0 , the densities of dark matter and dark energy. This makes the interpretation of the angular spectrum something of a complex undertaking, but it also makes it a sensitive probe of cosmological models and, implicitly, a particle physics laboratory of high precision [28].

Much later (~ 1 –10 Gyr), the small inhomogeneities generated during inflation have grown, via gravitational collapse, to become galaxies, clusters of galaxies, and superclusters, characterizing the epoch of *structure formation*. It is the realm of long–range gravitational physics, dominated by a dark (vacuum) energy. Finally (3 K, 13 Gyr), the Sun, the Earth, and biological life originated from previous generations of stars, and from a primordial soup of organic compounds, respectively.

The recent announcement by the WMAP satellite team of the landmark measurements of the CMB anisotropy [20] has convincingly confirmed important aspects of the current standard cosmological model described above.

4 Conclusions

We have entered a new era in cosmology and astrophysics, where a host of high-precision measurements are already posing challenges to our understanding of the Universe: the density of ordinary matter and the total amount of energy in the Universe; the microwave background anisotropies on a fine-scale resolution; primordial deuterium abundance from quasar absorption lines; the acceleration parameter of the Universe from high-redshift supernovae observations; the rate of expansion from gravitational lensing [29]; large-scale structure measurements of the distribution of galaxies and their evolution; and many more, which already put constraints on the parameter space of cosmological models.

However, these are only the forerunners of the precision era in cosmology that will dominate the new millennium, and make cosmology a phenomenological science, whose results can be incorporated into experimental high energy physics [30]. An impressive example of such a symbiosis of modern observational cosmology and experimental particle physics was the last improvement of the probe of the neutrino masses by 2dF galaxy redshift surveys data combined with WMAP results. The obtained limit [20] on the sum of the neutrino masses of 0.7 eV is substantially better than even the most stringent direct laboratory limit on any individual neutrino mass. On top of it, WMAP data also provide a new limit on the effective number of light neutrino species, beyond the three within the Standard Model [31]: $-1.5 < \Delta N_\nu^{eff} < 4.2$. This limit is not as stringent as that from LEP, but it applies to additional light particles, that might not be produced in Z decay. The cosmological upper limit on the masses of supersymmetric particles which can play the role of dark matter, is also improved by WMAP [32].

One of the most difficult challenges that the new cosmology will have to face is understanding the origin of the dark energy, whose behaviour is similar to that of the inflaton field, but 13 Gyr later [33]. It is of tremendous interest from the standpoint of fundamental theory [34]. In this sense cosmology provides us with a way to study a question of central importance for particle theory, namely the nature of the vacuum in quantum field theory. This is something that cannot be studied in particle accelerators, so in this sense cosmology provides a unique window on particle physics.

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